

Delayed pulsar kicks from the emission of sterile neutrinos

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The observed velocities of pulsars suggest the possibility that sterile neutrinos with mass of several keV are emitted from a cooling neutron star. The same sterile neutrinos could constitute all or part of cosmological dark matter. The neutrino-driven kicks can exhibit delays depending on the mass and the mixing angle, which can be compared with the pulsar data. We discuss the allowed ranges of sterile neutrino parameters, consistent with the latest cosmological and X-ray bounds, which can explain the pulsar kicks for different delay times.

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Observed velocities of pulsars [1] can be explained by an anisotropic emission of sterile neutrinos [2, 3, 4, 5] or other light particles [6]. Sterile neutrinos are firmly rooted in particle physics [7], because the gauge singlet (right-handed) neutrinos are needed to account for the observed neutrino masses in what is called the seesaw Lagrangian [8]. If some of the gauge singlets turn out to be light, they can appear below the electroweak scale as sterile neutrinos. There are further hints in favor of this intriguing possibility: in addition to explaining the pulsar kicks, sterile neutrinos with the same parameters could make up the cosmological dark matter [9, 10, 11, 12, 13] and could play an important role in the formation of the first stars [14]. This form of “warm” dark matter may be in good agreements with observational inferences regarding the small-scale structure [15, 16]. In contrast, the active neutrino oscillations cannot explain the pulsar kicks, unless they have very large magnetic moments [17], or the mass difference is large enough to allow the Mikheev-Smirnov-Wolfenstein [18] resonance at density $10^{11} - 10^{12} \text{ g/cm}^3$ [19, 20], which is excluded by the current data on neutrino masses.

The most promising way to discover sterile neutrinos is by observing X-ray photons from decays of the relic sterile neutrinos, which have lifetimes longer than the age of the universe but which can, nevertheless, produce a detectable signal [21]. The X-rays produced by the dark matter decays, and the production rate of sterile neutrinos in a supernova are both governed by two parameters: the sterile neutrino mass and the mixing angle. It is, therefore, important to understand the allowed ranges of these parameters. The range implied by the pulsar kicks can help focus the X-ray searches. In Ref. [3], the allowed range was discussed for both the resonance and the off-resonance production. In this paper we will reconsider this range of parameters, apply the present constraints from the X-ray observations and the Lyman-alpha bounds, and we will also relate the range of sterile neutrino masses and mixing angles to the delays in the onset of the kick. This delay can have some observable consequences and can be determined from the studies of

the pulsar populations [22].

In applying the cosmological constraints, we distinguish between two different issues: the particle’s existence and its ability to account for all of dark matter. Assuming the standard cosmology (rather than, e.g., the low-reheat cosmology [23]), one expects the neutrino oscillations to generate some out-of-equilibrium population of dark-matter particles that depends only on the mass and the mixing parameters. This population may constitute only a fraction of dark matter if the mixing angle is small enough. However, there are other ways in which the relic sterile neutrinos could be produced: for example, they can be produced from the inflaton decay [10] or from the decay of the Higgs boson at the electroweak scale [11]. The latter scenario produces a population of dark matter particles that is considerably “colder” [11] than the warm dark matter originating from neutrino oscillations, and the amount of dark matter is completely independent from the mixing angle. Nevertheless, regardless of any additional production mechanisms, the production by oscillations cannot be “turned off” (except for non-standard cosmological scenarios [23]). Therefore, there exists a robust cosmological bound on the mass and mixing angle, which is based on the effects of sterile neutrinos produced by oscillations, even if they do not make up all the dark matter.

We, therefore, show two exclusion regions in Fig. 1. In the solid “excluded region”, the existence of a sterile neutrino conflicts with the assumptions of standard cosmology. Below this region, but above the dashed line, the particle may exist, but it may not account for all the dark matter because of the existing X-ray bounds [21]. Finally, below the dashed line, the particle may exist and may account for all dark matter. As one can see from the figure, the resonant mechanism is inconsistent with all dark matter being sterile neutrinos, but is a viable explanation for the pulsar kicks, as long as the sterile neutrinos make up only a part of dark matter. In contrast, the off-resonant mechanism is consistent with all of dark matter being in the form of sterile neutrinos.

In a supernova, the sterile neutrinos are produced in

two ways: the active neutrinos can oscillate into the sterile neutrinos on resonance [2], or off-resonance [3]. In both cases, they escape anisotropically because the electrons and other fermions in the newly formed neutron star are polarized in the magnetic field. Of course, the ordinary neutrinos are produced with some anisotropy as well, but their production asymmetry is completely washed out by the numerous scatterings the neutrinos undergo on their way out of the star as they diffuse in approximate thermal equilibrium [20]. In contrast, the sterile neutrinos escape without scatterings, with the emission asymmetry equal their production asymmetry, because their scattering cross section is suppressed by the small mixing angle.

In the case of the production off resonance, the allowed range of parameters has a direct connection with the time delay from the supernova collapse until the onset of the kick. In the case of production on resonance, the connection is less obvious. While there are many uncertainties in the supernova parameters, we think it is of interest to show the parametric dependence of the allowed kick parameters on time delay.

Let us briefly summarize the results of Ref. [3]. The off-resonance production rate of sterile neutrinos is determined by the mixing angle in matter θ_m , which, in general is not the same as the mixing angle θ in vacuum:

$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V_m)^2}, \quad (1)$$

where the matter potential V_m is positive (negative) for $\nu(\bar{\nu})$, respectively; p is the momentum. For the case of ν_e oscillations into sterile neutrinos,

$$V_m = \frac{G_F \rho}{\sqrt{2} m_n} (3Y_e - 1 + 4Y_{\nu_e} + 2Y_{\nu_\mu} + 2Y_{\nu_\tau}). \quad (2)$$

In a core collapse supernova, the initial value of this matter potential is $V_m \simeq (-0.2... + 0.5)V_0$, where V_0 depends on the density ρ ; $V_0 = G_F \rho / \sqrt{2} m_n \simeq 3.8 \text{ eV}(\rho/10^{14} \text{ gcm}^{-3})$.

It was pointed out in Ref. [12] that, in the presence of sterile neutrinos, rapid conversions between different neutrino flavors can drive the effective potential to its stable equilibrium fixed point

$$V_m \rightarrow 0. \quad (3)$$

This equilibration takes place on a time scale

$$\begin{aligned} \tau_v &\simeq \frac{4\sqrt{2}\pi^2 m_n}{G_F^3 \rho} \frac{(V_m^{(0)})^3}{(\Delta m^2)^2 \sin^2 2\theta} \frac{1}{\mu^3} \\ &\sim \frac{10^{-9} \text{ s}}{\sin^2 \theta} \left(\frac{V_m^{(0)}}{0.1 \text{ eV}} \right)^3 \left(\frac{50 \text{ MeV}}{\mu} \right)^3 \left(\frac{10 \text{ keV}^2}{\Delta m^2} \right)^2. \end{aligned} \quad (4)$$

Once the equilibrium is achieved at $V_m \approx 0$, the effective mixing angle in matter is close to that in vacuum, and from this point on the emission of sterile neutrinos proceeds at a much higher rate.

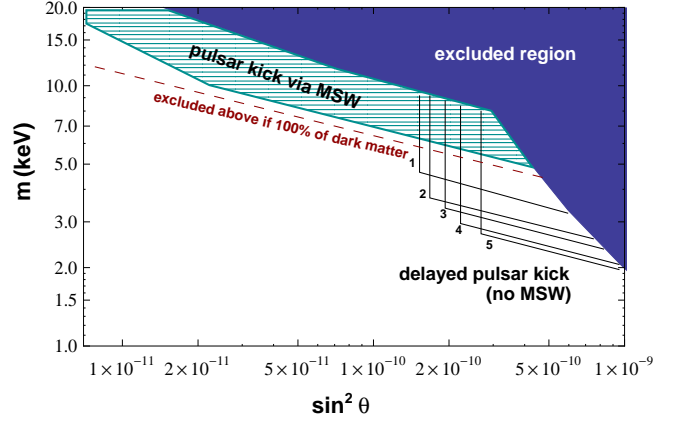


FIG. 1: The allowed regions for delayed kicks with delays from 1 through 5 seconds (assuming the other parameters are fixed) are shown by black solid lines marked by the numbers representing the delay time in seconds. The exclusion region is based on the combination of the X-ray bounds and the Lyman- α bounds, according to Palazzo et al. [13]. Here we distinguish between the two possibilities: (i) sterile neutrino with a given mass and mixing angle may exist, and (ii) sterile neutrino with a given mass and mixing angle may constitute the entire cosmological dark matter. The former possibility is viable for all the points below the solid “excluded region”, while the latter is limited from above by the dashed line (see discussion in the text). These bounds can be evaded in low-reheat cosmologies [23].

There is a considerable uncertainty in the equilibration time given by eq. (5) because several parameters are functions of time and position in the star and are not known precisely. The equilibration does not have to occur simultaneously in the entire star. However, although the emission of both active and sterile neutrinos is subject to much uncertainty, the total energy must be close to the initial gravitational energy of the collapsing core, $3 \times 10^{53} \text{ erg}$. It is also known that at least 30% of this energy must be carried out of the supernova by ordinary neutrinos to explain the observed neutrino signal from SN1987A. Finally, if the sterile neutrinos are to explain the pulsar kicks, they must carry a non-negligible fraction \mathcal{E}_s of the total energy \mathcal{E}_{tot} [3]:

$$r_{\mathcal{E}} = \left(\frac{\mathcal{E}_s}{\mathcal{E}_{\text{tot}}} \right) \approx 0.25. \quad (5)$$

This results in a 1% anisotropy of the overall neutrino emission and give the pulsar a kick consistent with observations.

The relative rates of the active and sterile neutrino production depend on the mixing angle θ and the temperatures in the core (where the sterile neutrinos are produced) and the neutrinosphere (from where the active neutrinos are emitted). In addition, the time interval over which the sterile neutrinos are emitted can be shortened if the equilibration of $V_m \rightarrow 0$ takes some non-negligible time. Based on the discussion of Ref. [3], one

can estimate the ratio $(\mathcal{E}_s/\mathcal{E}_{\text{tot}}) = \mathcal{E}_s/(\mathcal{E}_s + \mathcal{E}_\nu)$ as follows:

$$\left(\frac{\mathcal{E}_s}{\mathcal{E}_\nu}\right) \sim \sin^2 \theta \left(\frac{T_{\text{core}}}{T_{\nu\text{-sphere}}}\right)^6 \left(\frac{t - \tau_\nu}{t}\right) f_M f_{\text{d.o.f.}}, \quad (6)$$

where $f_M < 1$ is the fraction of enclosed mass of the core from which the emission of sterile neutrinos is efficient, and $f_{\text{d.o.f.}} \geq 1$ is an enhancement due to a possible increase in the effective degrees of freedom at high density [25].

Using eqs. (5) and (6) one can find the minimal mixing angle consistent with $r_\mathcal{E} \geq 0.25$. The minimal allowed value of the mixing angle corresponds to the maximal allowed value of the ratio of these two temperatures, $T_{\text{core}}/T_{\nu\text{-sphere}}$. The neutrinosphere temperature $T_{\nu\text{-sphere}} = 2 - 5$ MeV [24, 25, 26] is determined by the heat exchange due to neutrino cooling near the surface of last scattering. This temperature has very little dependence on the nuclear equation of state and is almost entirely determined by the conditions around the neutrinosphere, *i.e.* at density of the order of $10^{11} - 10^{12}$ g/cm³ [24, 25, 26]. In contrast, the core temperature depends on the nuclear equation of state at densities $\rho \gg 10^{14}$ g/cm³ and can vary dramatically, depending on the assumptions about nuclear matter [25, 26]. With a few exceptions, the models listed in Tables of Ref. [26] predict the core temperatures $T_{\text{core}} < 100$ MeV, and the majority of these models show the temperatures in the range $T_{\text{core}} \approx (20 - 70)$ MeV [26]. We will adopt the latter as the allowed range of the core temperatures.

Since there is little or no correlation between the core temperature and the neutrinosphere temperature, we allow the ratio $T_{\text{core}}/T_{\nu\text{-sphere}}$ vary between the lowest and the highest value for $T_{\nu\text{-sphere}} = 2 - 5$ MeV and $T_{\text{core}} \approx (20 - 70)$ MeV. The large uncertainty in the ratio of temperatures is the reason for the broad allowed range of masses and mixing angles. The corresponding

contours are shown in Fig. 1 for different values of the time delay. The longer time delays correspond to lower mass for the same mixing angle. However, since the time available for the kick is shorter, the minimal mixing angle increases for longer delays (see Fig. 1).

The neutrino-driven kicks have several predictions, in addition to time delays, that can be tested using the astronomical observations. The neutrino kick mechanism does not predict a correlation between the magnitude of the surface magnetic fields and the pulsar velocity (the “ $B - v$ ” correlation) [5]. The kick velocity is determined by the magnetic field inside the hot neutron star during the first seconds after the supernova collapse. In contrast, the astronomical observations can be used to infer the surface magnetic fields of pulsars some millions of years later. The relation between the two is highly non-trivial because of the complex evolution the magnetic field undergoes in a cooling neutron star. However, the correlation of the direction of the spin axis and the direction of the pulsar velocity is a generic prediction of this mechanism [5, 27]. Such a correlation is confirmed by recent observations [28]. In the event of a nearby supernova, the neutrino kick can produce gravity waves that could be detected by LIGO and LISA [29, 30]. Finally, the neutrino-driven kicks can increase the energy of the supernova explosion because they enhance the convection in front of the moving neutron star and increase the energy of the shock wave [31], and also because they deposit entropy ahead of the shock [32]. The increase of convection in front of the moving neutron star can produce asymmetric jets with the stronger jet pointing in the direction of the pulsar motion, in contrast with what one could expect from other kick mechanisms [31].

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